Long-term multi-wavelength variability of Markarian 421 and Markarian 501

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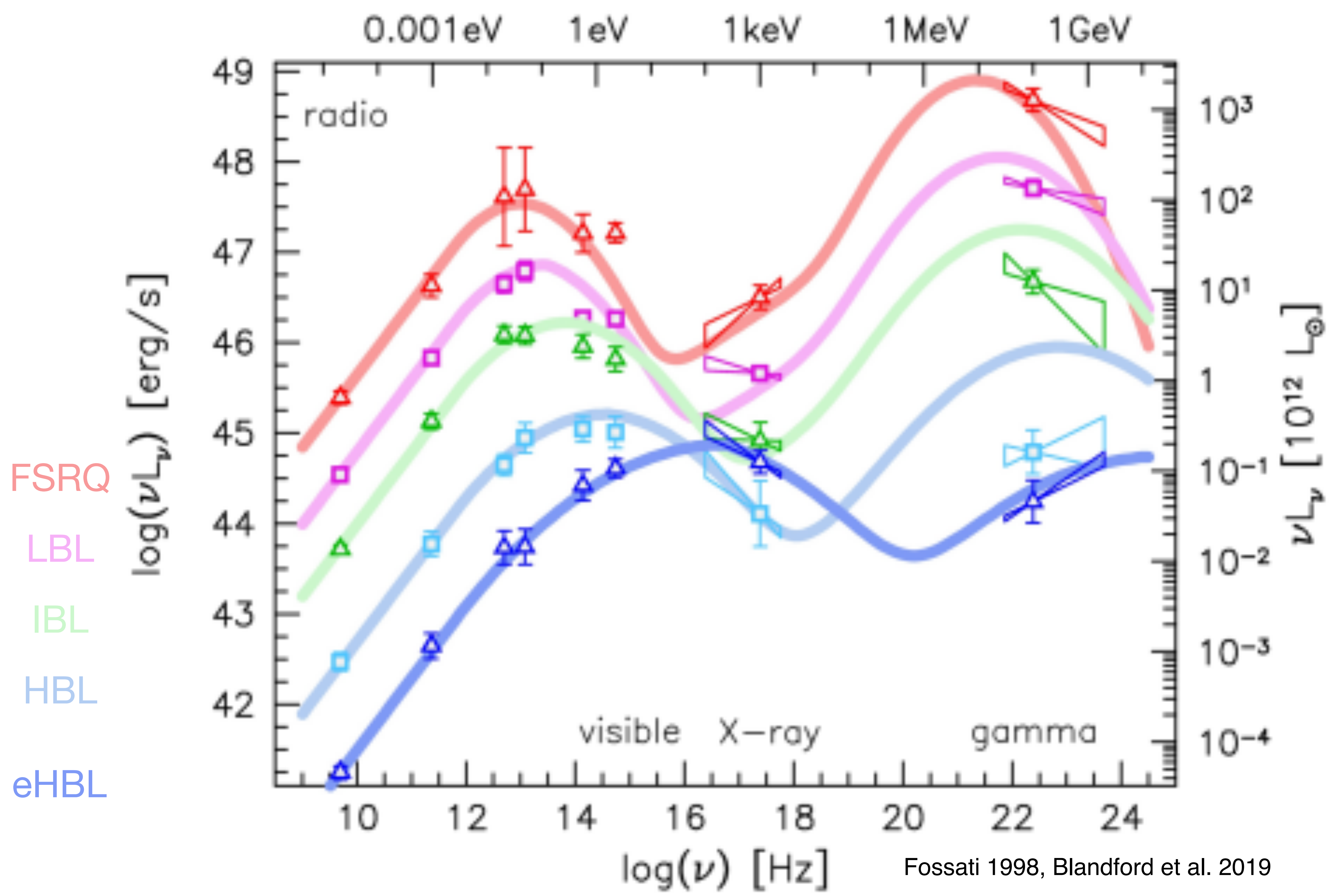
TeVPA 2021

Image credit: DESY, Science Communication Lab

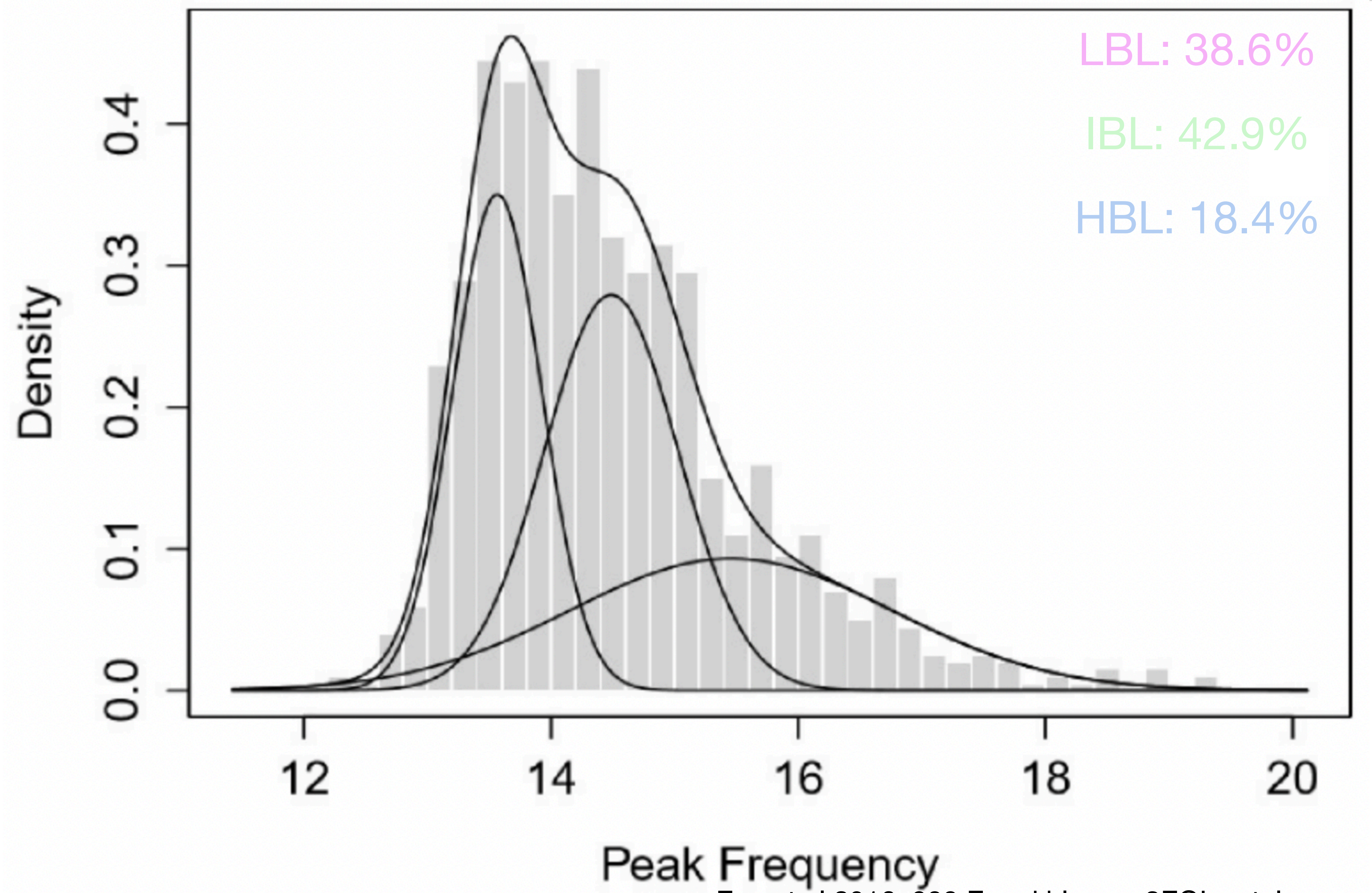
AGNs: blazars

- Blazars are radio loud AGNs with jet pointing to Earth:
  - Flat radio spectrum, radio loud
  - Emission is Doppler boosted and relativistically beamed
  - Blazars emit from radio to VHE gamma-rays
  - Optical emission is polarised
  - Emission is variable on different timescale
  - Emission in different bands may have a delay relatively to others

- Classification of blazars depending on synchrotron hump location: LBL, IBL, HBL and extreme-HBL (eHBL)
  - Padovani & Giommi 1996: LBL $\nu_p < 10^{15}$, HBL $\nu_p > 10^{15}$
  - Nieppola et al. 2006: LBL $\nu_p < 10^{14.5}$, IBL $10^{14.5} < \nu_p < 10^{16.5}$, HBL $\nu_p > 10^{16.5}$
  - Abdo et al. 2010: LBL $\nu_p < 10^{14}$, IBL $10^{14} < \nu_p < 10^{15}$, HBL $\nu_p > 10^{15}$



Fossati 1998, Blandford et al. 2019

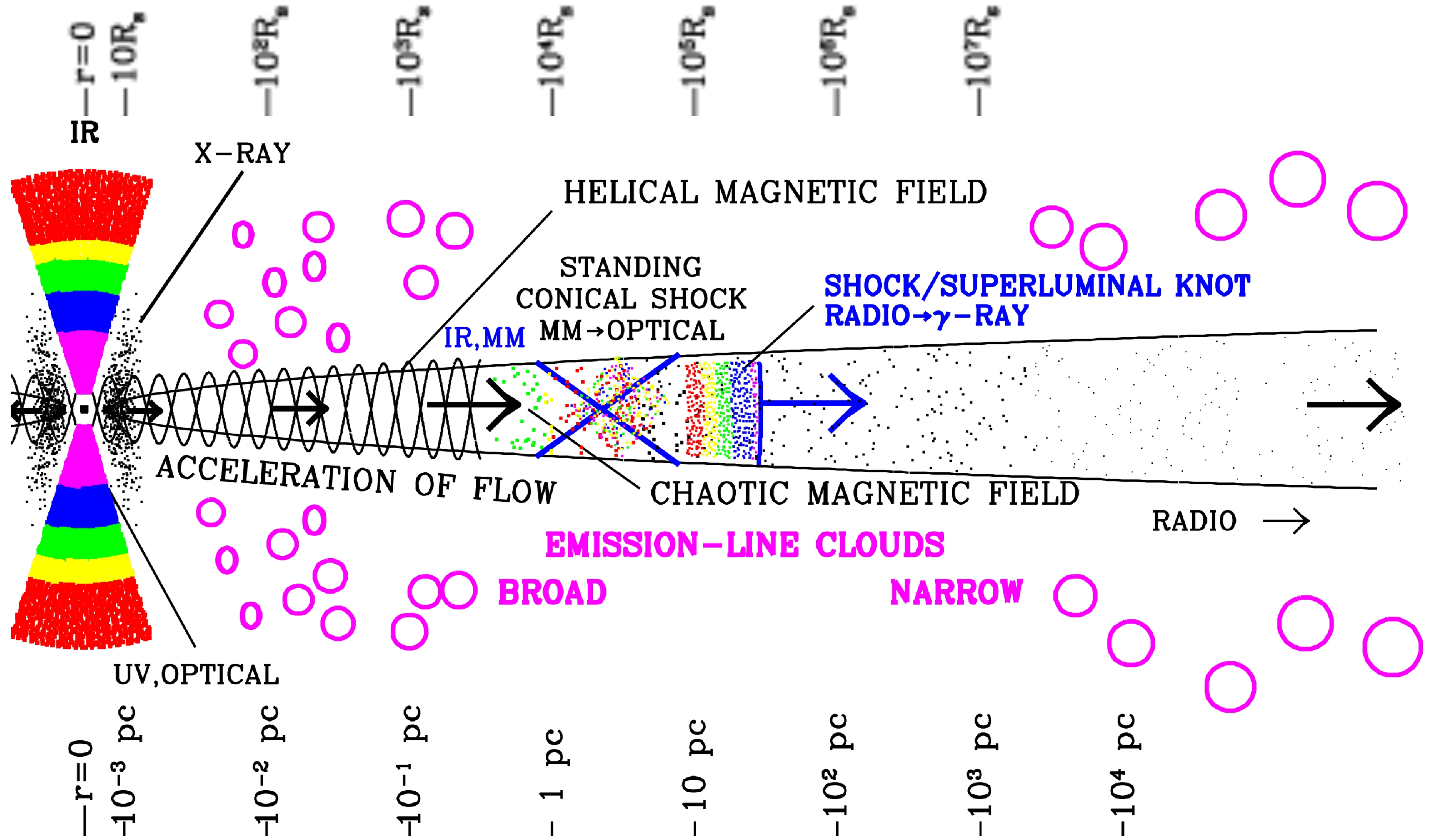


Fan et al 2016, 999 Fermi blazars 3FGL catalogue

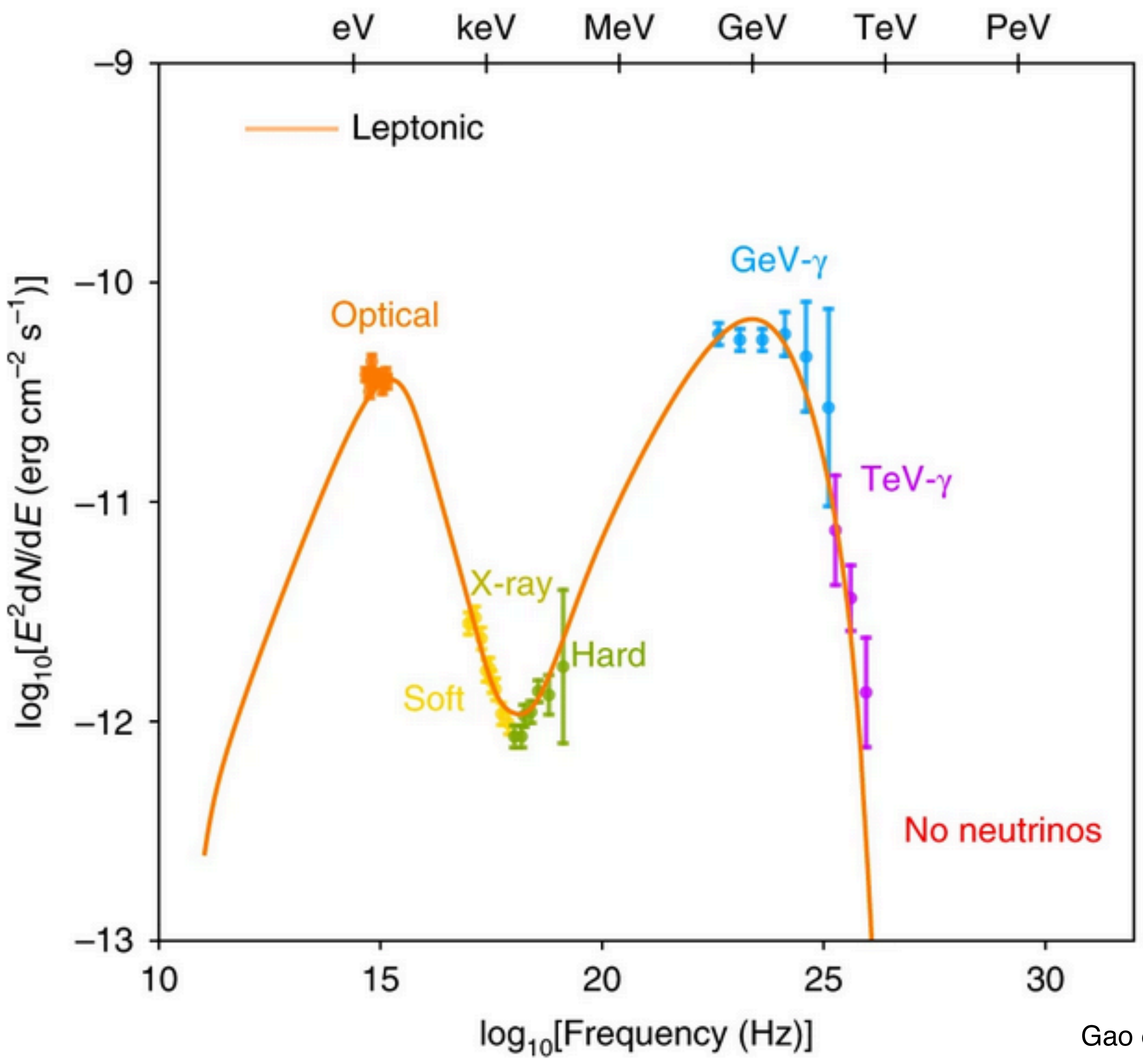
Emission mechanisms

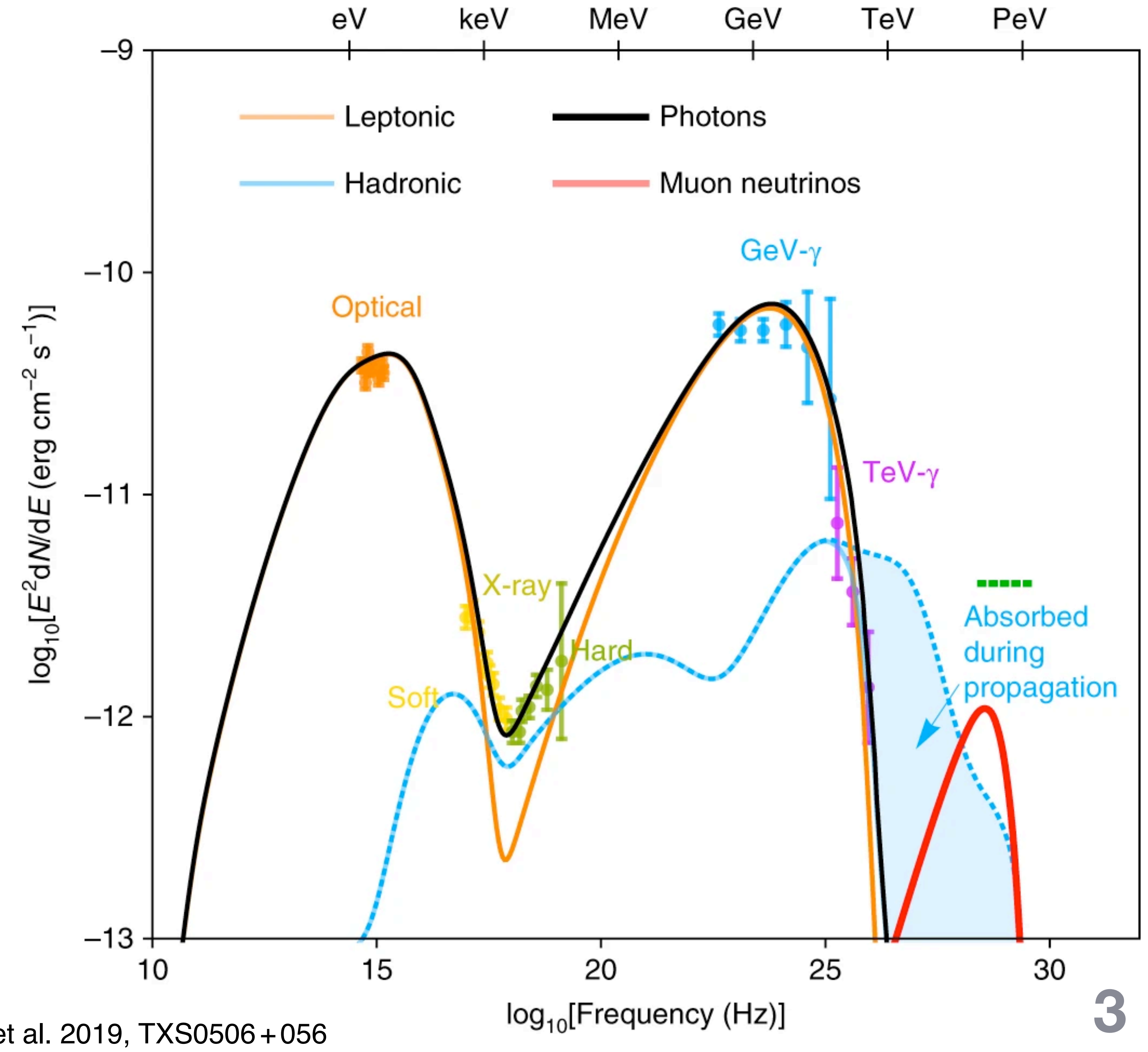
- Particle acceleration
  - Diffusive shock acceleration
  - Relativistic reconnections
  - Stochastic acceleration
  - Magnetoluminescence

- Radiative processes
  - Leptonic: ultraletivistic electrons, synchrotron and IC radiation
  - Handronic: proton-synchrotron, pion photoproduction
  - Lepto-hadronic: mixture of leptonic and hadronic



Marscher et al., http://www.bu.edu/blazars/

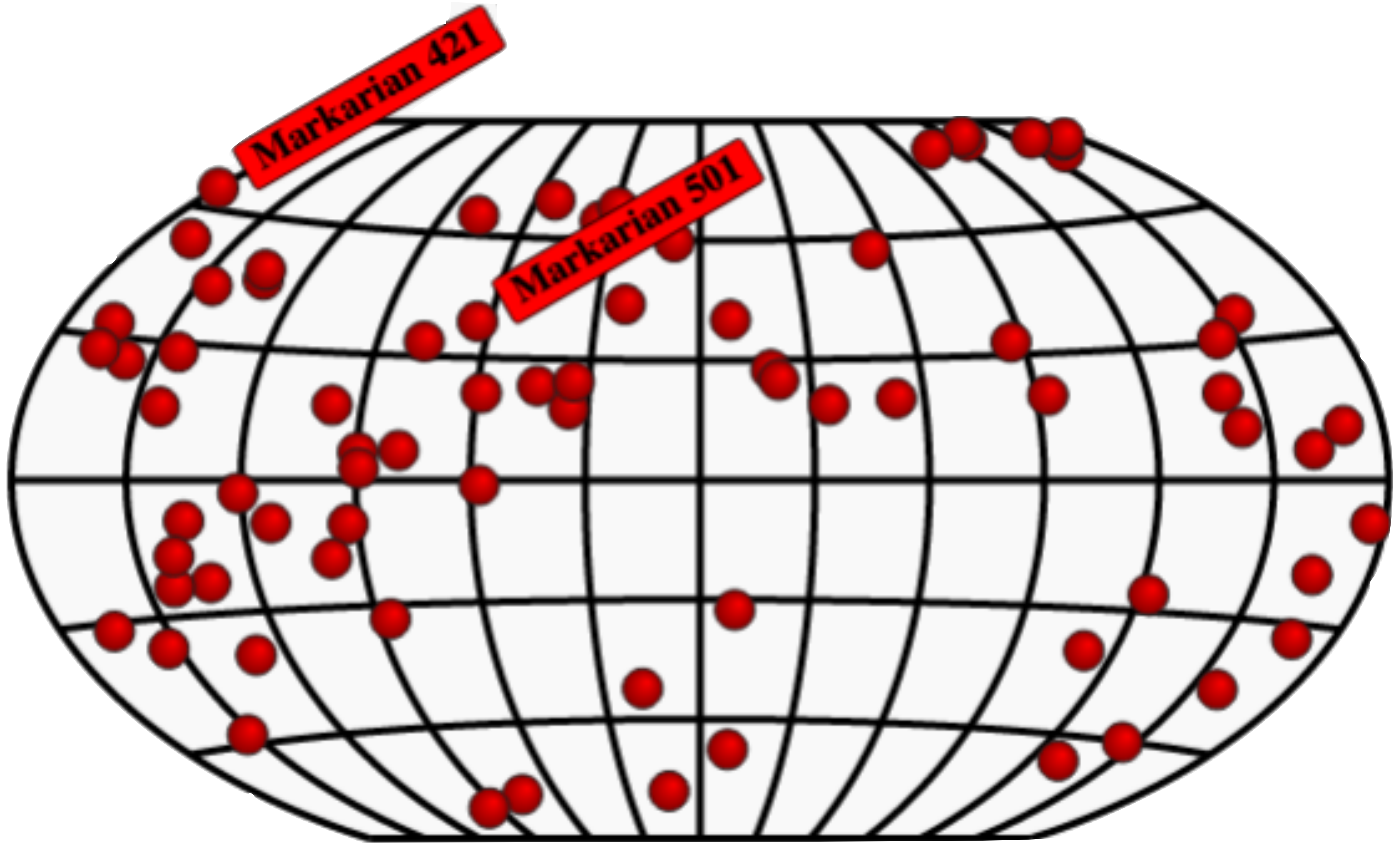




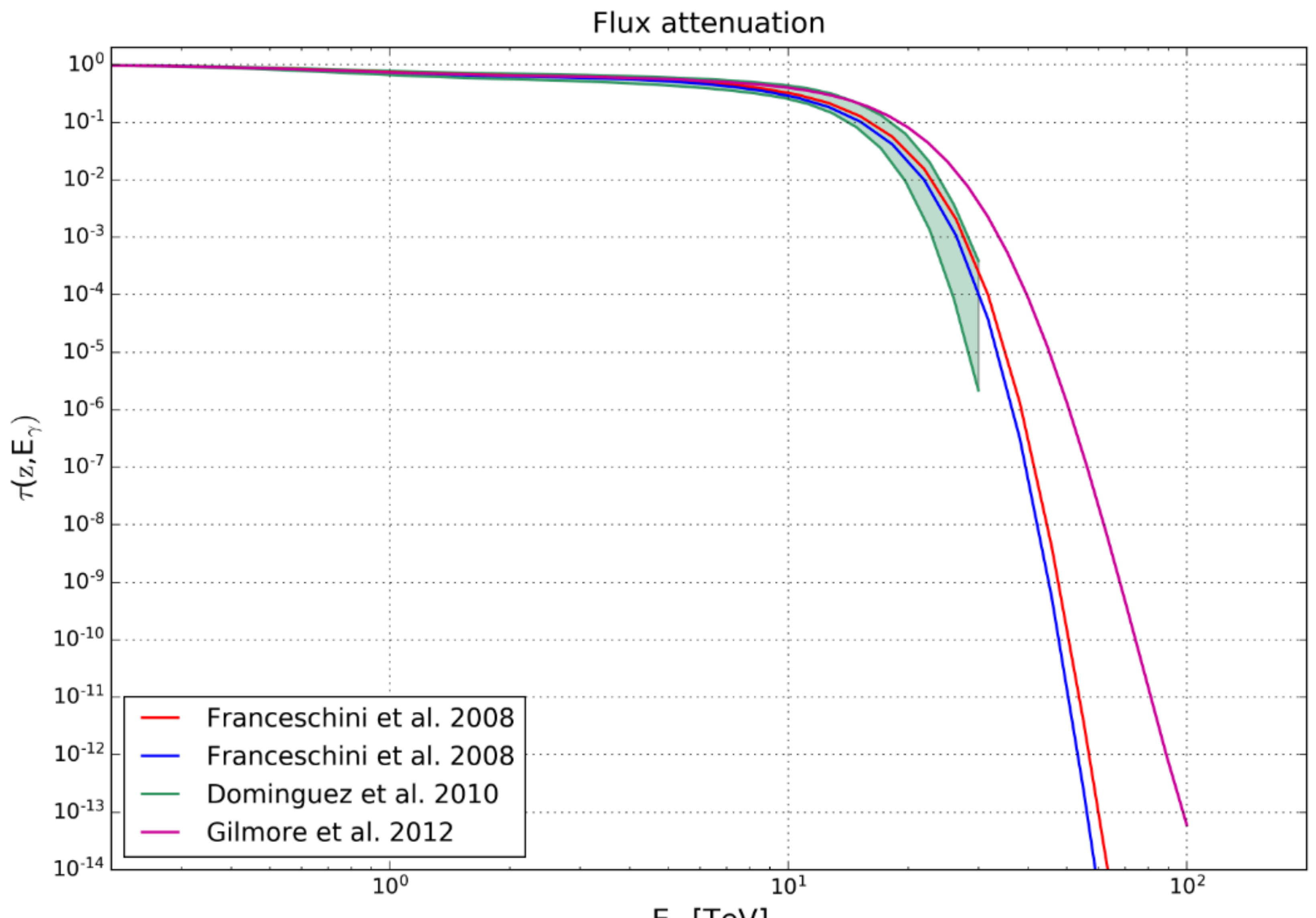
Gao et al. 2019, TXS0506+056

Why Mrk 421 and Mrk 501?

- Bright blazars
  - Easy to detect with IACTs, Fermi, in X-rays, optical and radio
    - Regular observations in TeV (MAGIC, FACT*), optical and radio
  - Relatively easy to characterize the entire SED during single "observation"
    - Evolution of SED over time during individual flares
- No strong BLR effects
  - Less additional uncertainties than for FSRQs
- Nearby blazars (z ~ 0.03, ~140 Mpc)
  - Imaging with VLBI (MOJAVE, VLBA) down to scales of 0.01 pc (100 - 1000 R_s)
  - Minimal effect from EBL (which is not well known, and introduces systematics for VHE blazar science)



TeVCat



Organokov 2019

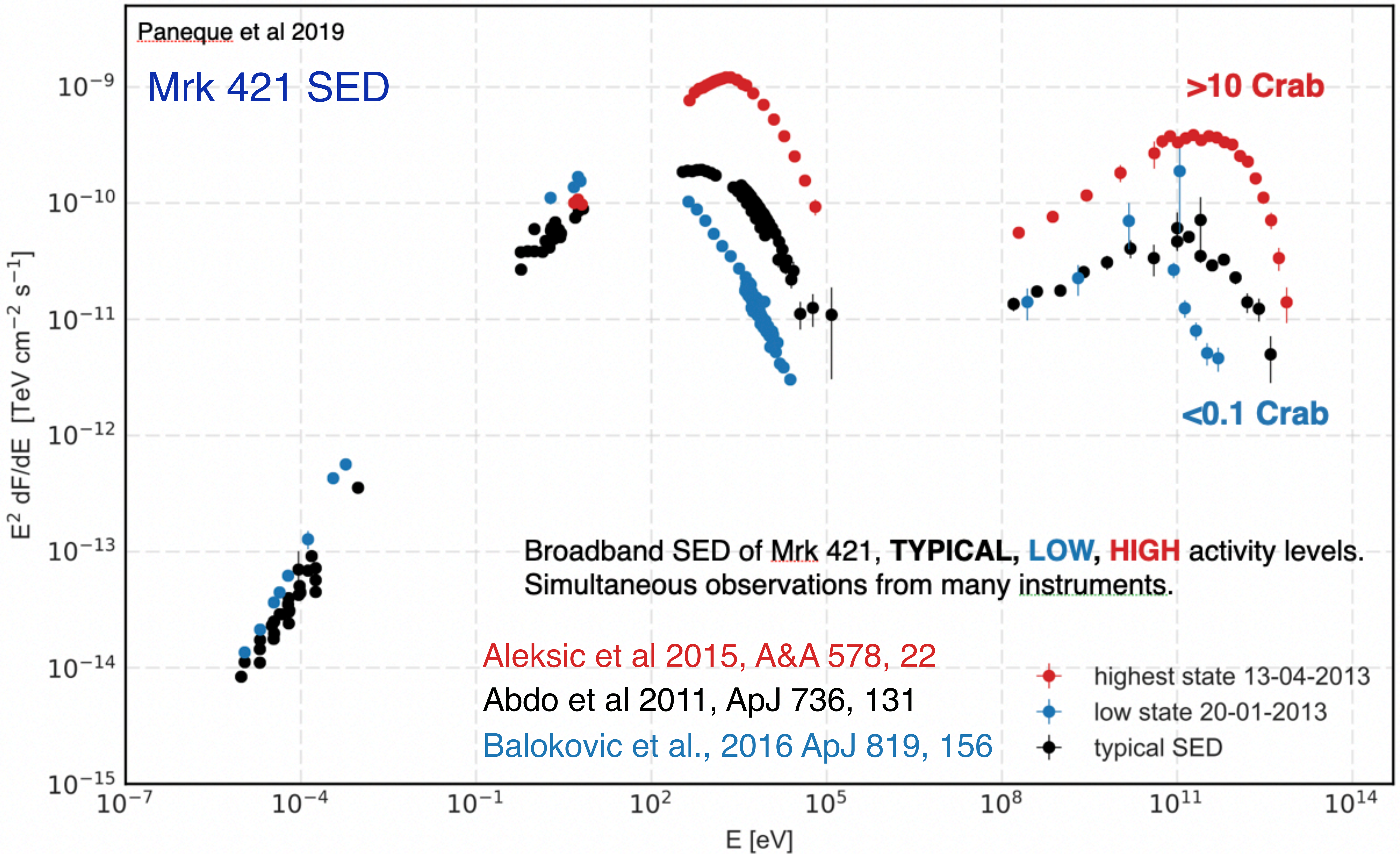
Mrk 421 & Mrk 501: overview

- Mrk 421 is a close HBL blazar
  - Bright and nearby blazar, z=0.031 (~122-133 Mpc)
  - $M_{BH} \sim 1.5\text{-}2.5 \times 10^8 M_\odot$
  - Imagined with VLBA up to <0.01-0.1 pc (<100-1000 rg)
  - Well defined jet structure extending for 4.5 mas (2.67 pc)
- Low energy hump:
  - synchrotron emission during relativistic electrons cooling
- High energy hump:
  - leptonic models:
    - one-zone SSC model (Celotti et al. 1998, Abdo et al. 2011)
    - multi-zone SSC model (Aleksić et al. 2015, Zhu et al. 2016)
  - hadronic models (Zech et al. 2017)
  - lepto-hadronic models:
    - synchrotron-proton model (Mastichiadis, Petropoulou 2013)
    - neutrino emission (Petropoulou 2015, Dermer Razzaque 2010)
  - etc.

- Mrk 501 is a close HBL blazar
  - Bright and nearby blazar, z=0.034 (~140 Mpc)
  - $M_{BH} \sim 2\text{-}9 \times 10^8 M_\odot$
  - Imagined with VLBA up to <0.01-0.1 pc (<100-1000 rg)
  - Well defined jet structure extending for 10-20 mas (~10 pc)
- Low energy hump:
  - synchrotron emission during relativistic electrons cooling
- High energy hump:
  - leptonic models:
    - one-zone SSC model (Ahnen et al. 2017, Acciari et al. 2020)
    - multi-zone SSC model (Ahnen et al. 2017, Acciari et al. 2020)
  - hadronic models (Mastichiadis et al. 2013, Zech et al. 2017)
  - lepto-hadronic models:
    - synchrotron-proton model (Mücke & Protheroe 2001)
    - neutrino emission (Petropoulou 2015, Dermer Razzaque 2010)
  - etc.

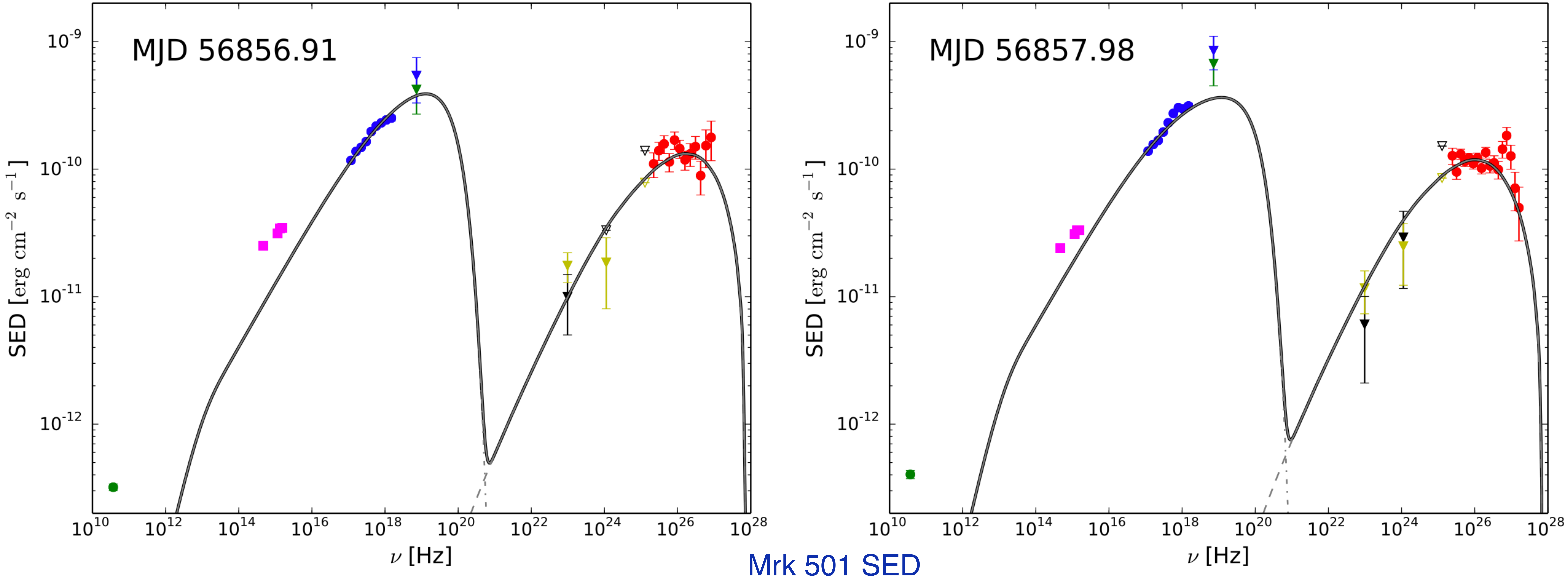
Mrk 421: temporal and spectral variability

- Mrk 421 is a target of numerous MW campaigns:
  - Synchrotron peak shifts between IBL (MW 2013) and HBL
  - One-zone SSC reasonably describes SED of Mrk 421
  - Flaring activity can also be described by two-zone SSC: one zone producing quiescent emission and another smaller zone producing intraday variability
- Variability:
  - Highest in X-rays and VHE
  - Substantial variability in optical though not correlated with X-rays and VHE
  - Persistently low variability in radio and GeV
  - Intra-day variability in X-rays and VHE for typical and high states
  - Variability observed on sub-hour timescales on the top of flux variations occurring on multi-hour timescales (Acciari et al, 2020 ApJS 248, 29)
- MW correlations:
  - Optical and radio are widely and strongly correlated
  - No correlation between the GeV band and the keV or TeV band
  - Linear correlation between X-rays 2-10 keV and VHE above 200 GeV
  - No delays between the X-ray and VHE gamma-ray emissions (down to 3 minutes during April 15, Acciari+2020)



Mrk 501: temporal and spectral variability

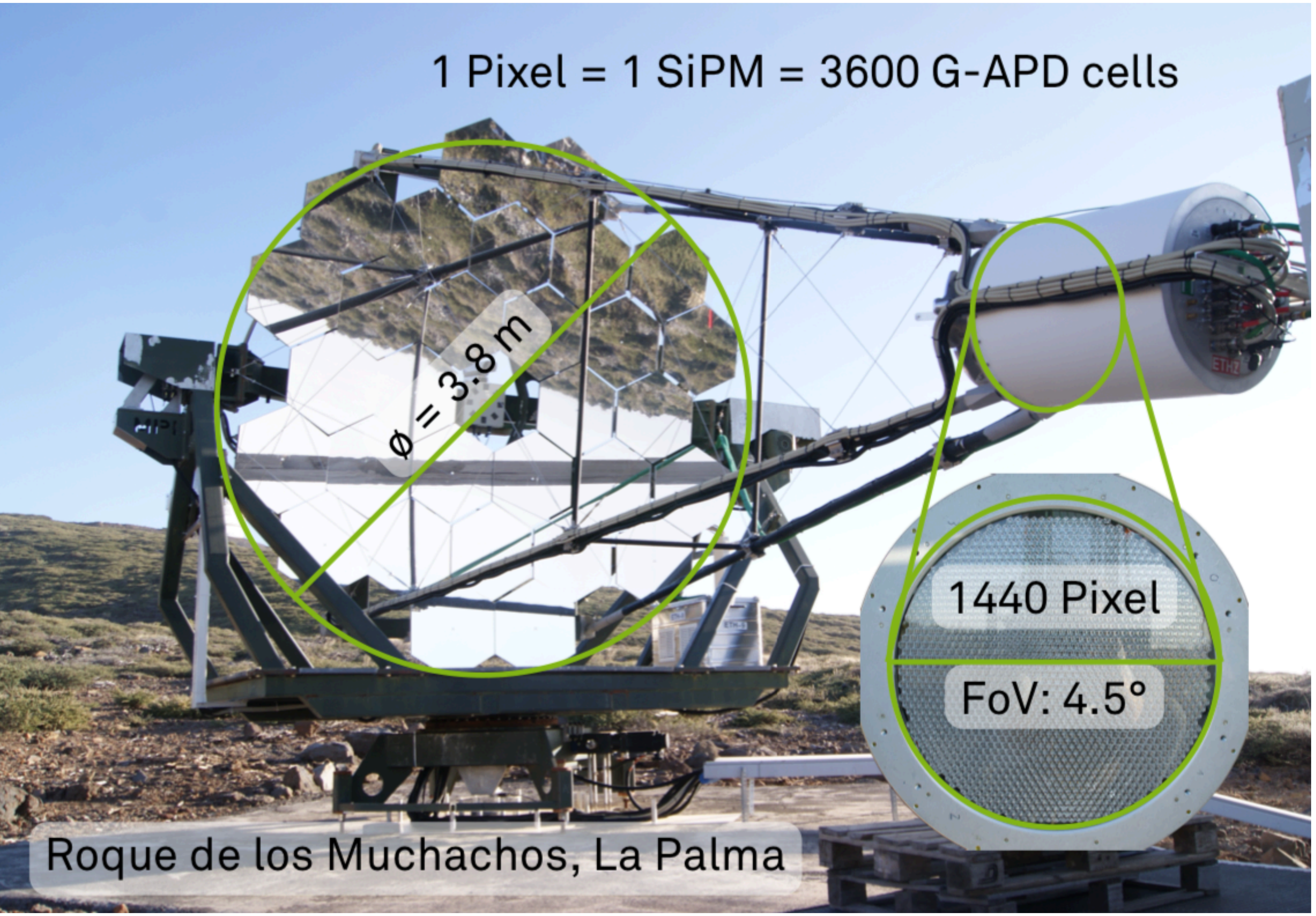
- Mrk 501 is a target of numerous MWL campaigns
- Mrk 501 shows spectral variability in X-rays and VHE during flares
  - becoming eHBL during some flares
  - one-zone SSC generally does a good job, but introduction of a second small region may be necessary to describe a feature at 3 TeV



Mrk 501 SED

MW 2014, Acciari et al. (2020)

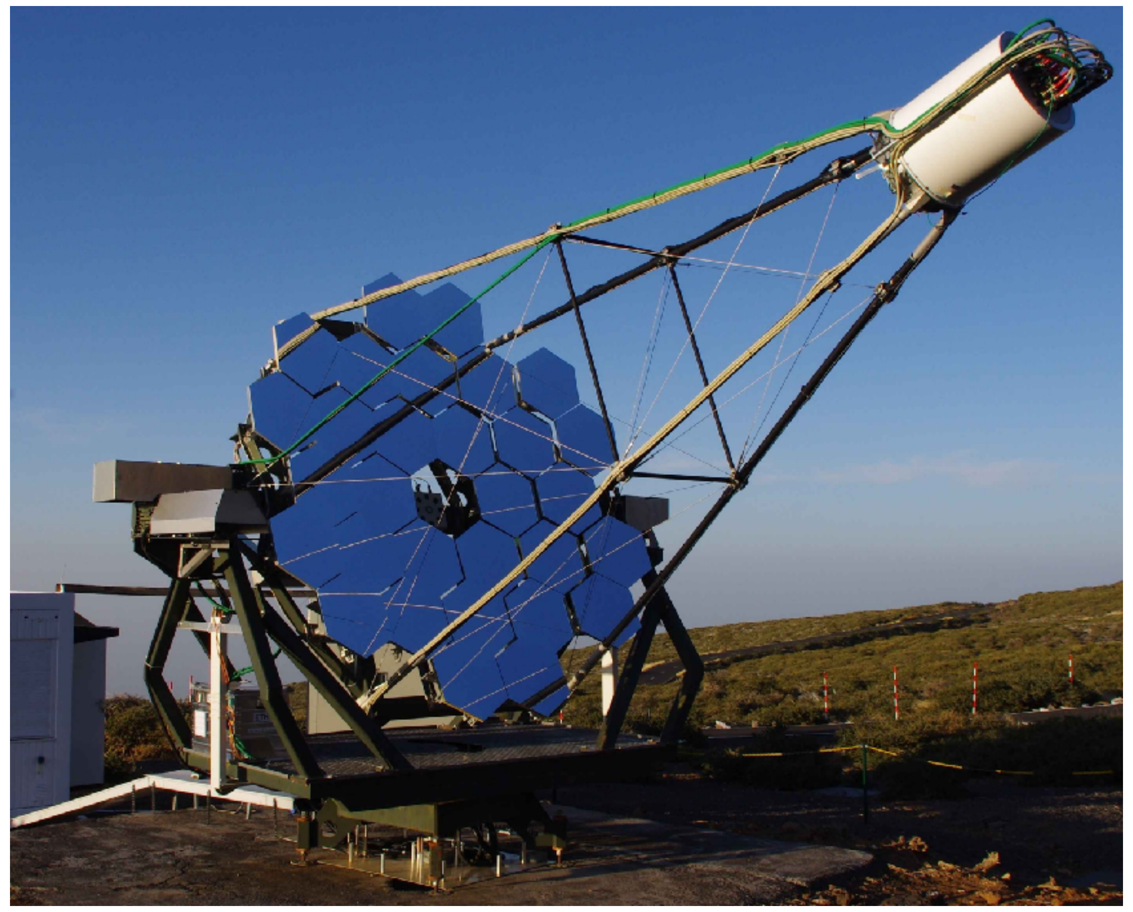
FACT: First G-APD Cherenkov Telescope

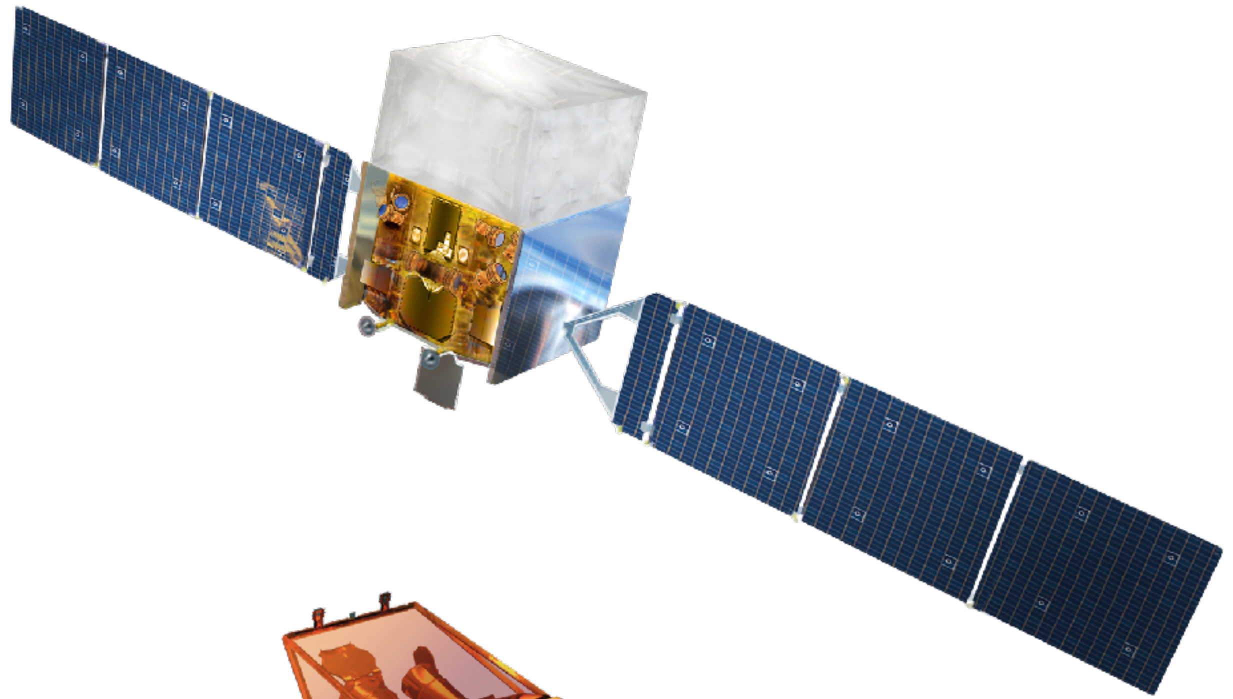


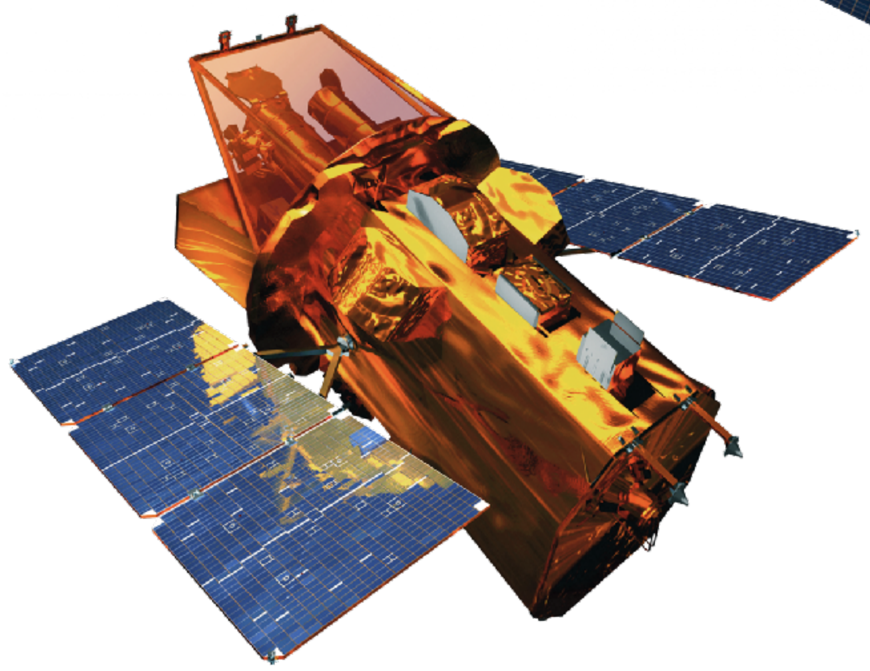
- Operates since October 2011 at La Palma, Roque de Los Muchachos, 2200 m a.s.l.
- Mirror area: 9.5 m^2 (⌀3.8 m)
- Camera FOV 4.5°, comprised of 1440 pixels (0.11° / pixel)
- Silicon based photo sensors (G-APDs): observations with strong moon light possible
- Operated fully remotely and automatically, large duty cycle (>2500h of data in 12 months)
- Integrated sensitivity: 0.137 ± 0.004 Crab / 50h
- Unbiased monitoring strategy:
  - Blazars, AGNs: Mrk 421, Mrk 501, 1ES 2344+51.4, 1ES 1959+650
  - Crab Nebula
  - Multi-Messenger and MWL alerts, e.g. AMON20160218, HESE20160427, HESE20160731, V404 Cyg.
- Quick Look Analysis to check source activity and generate ATels

Multi-wavelength campaign

FACT
First G-APD Cherenkov Telescope

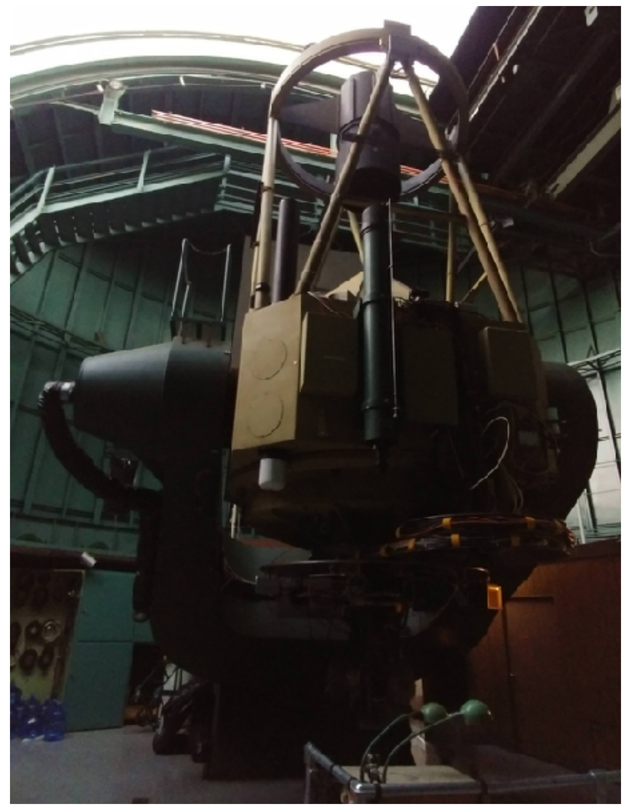


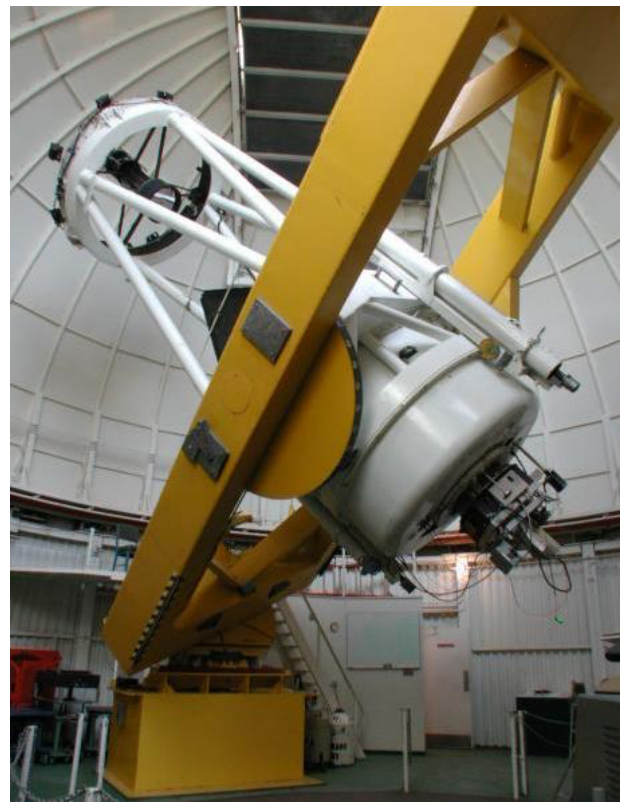




December 14, 2012 - April 18, 2018

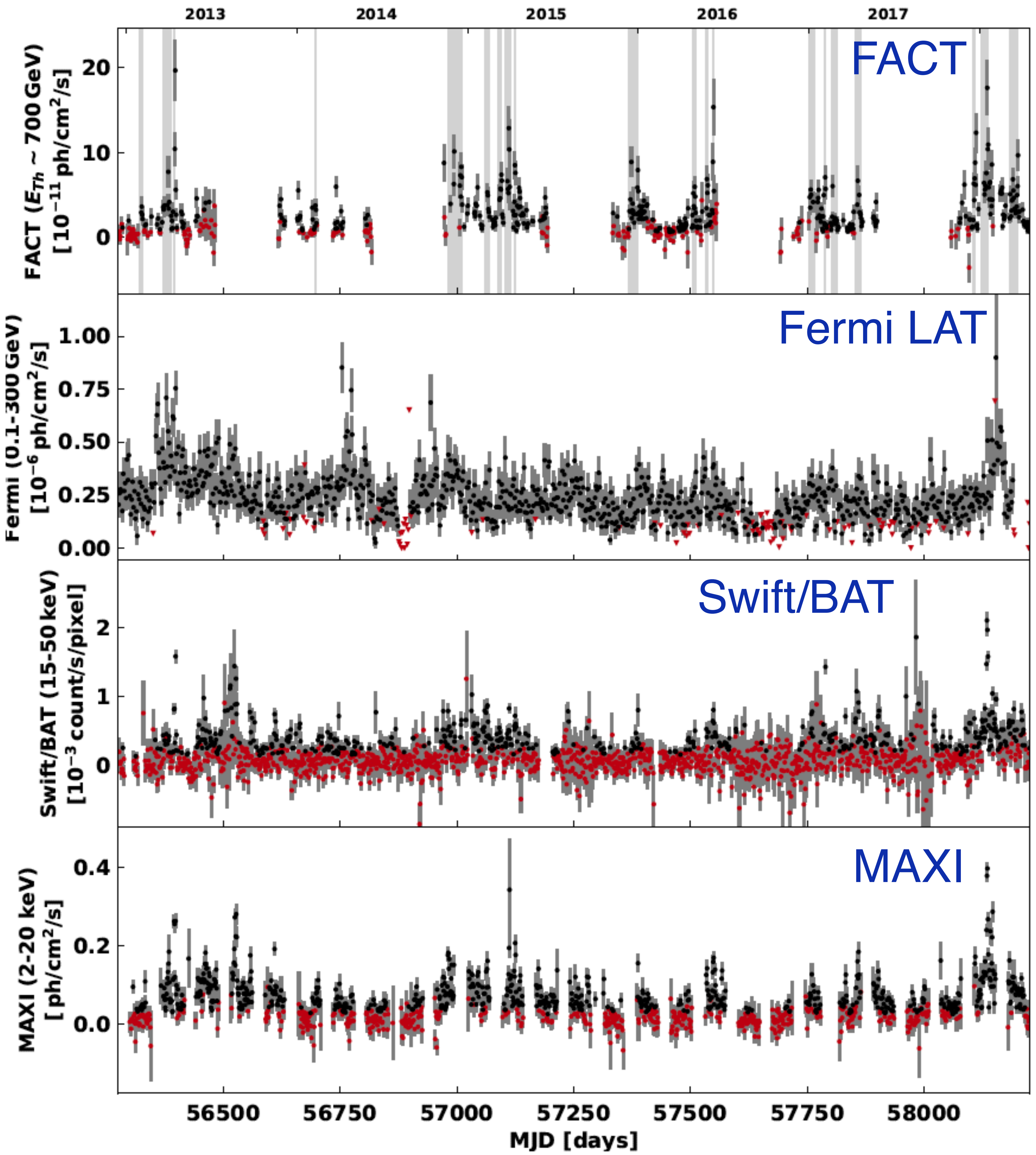
Instrument	Band	Mrk 421	Mrk 501
Fact	> 580 GeV	584 nights / 2071 hours	630 nights / 1783 hours
Fermi LAT	100 MeV - 300 GeV	1915 days	1793 days
Swift/BAT	15-50 keV	1706 days	1733 days
MAXI	2-20 keV	1181 days	-
Swift/XRT	0.3-2 keV, 2-10 keV	478 days / 652 hours	285 days/246 hours
Swift/UVOT	UV (UVW1, UVM2, UVW2 filters)	752 measurements	298 measurements
Kuiper (1.54m) & Bok (2.3m)	V-band	379 measurements	283 measurements
OVRO (40m)	15 Ghz	329 measurements	221 measurements

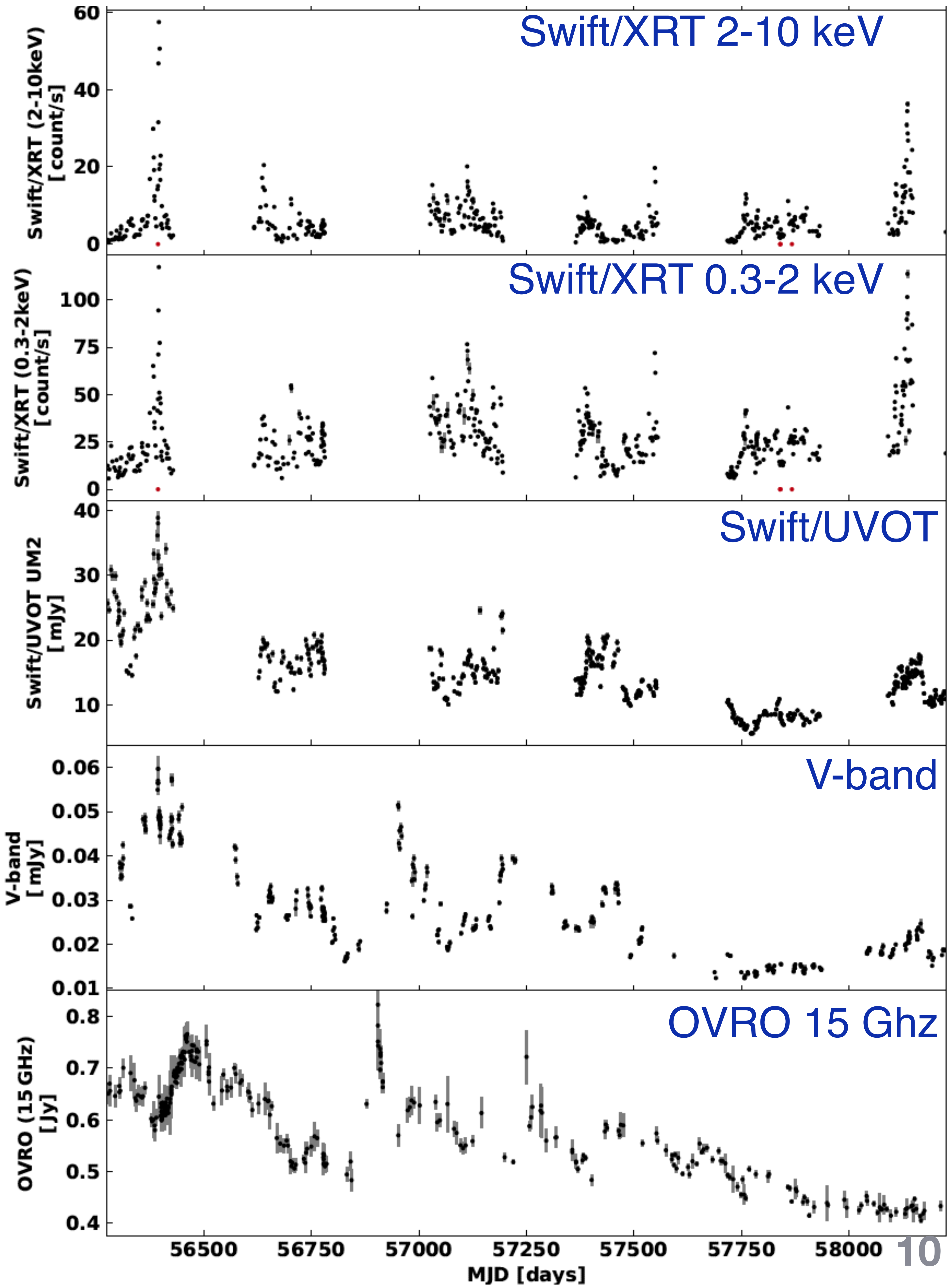




MWL campaigns: Arbet-Engels+MB+VS+RW, A&A, 2021

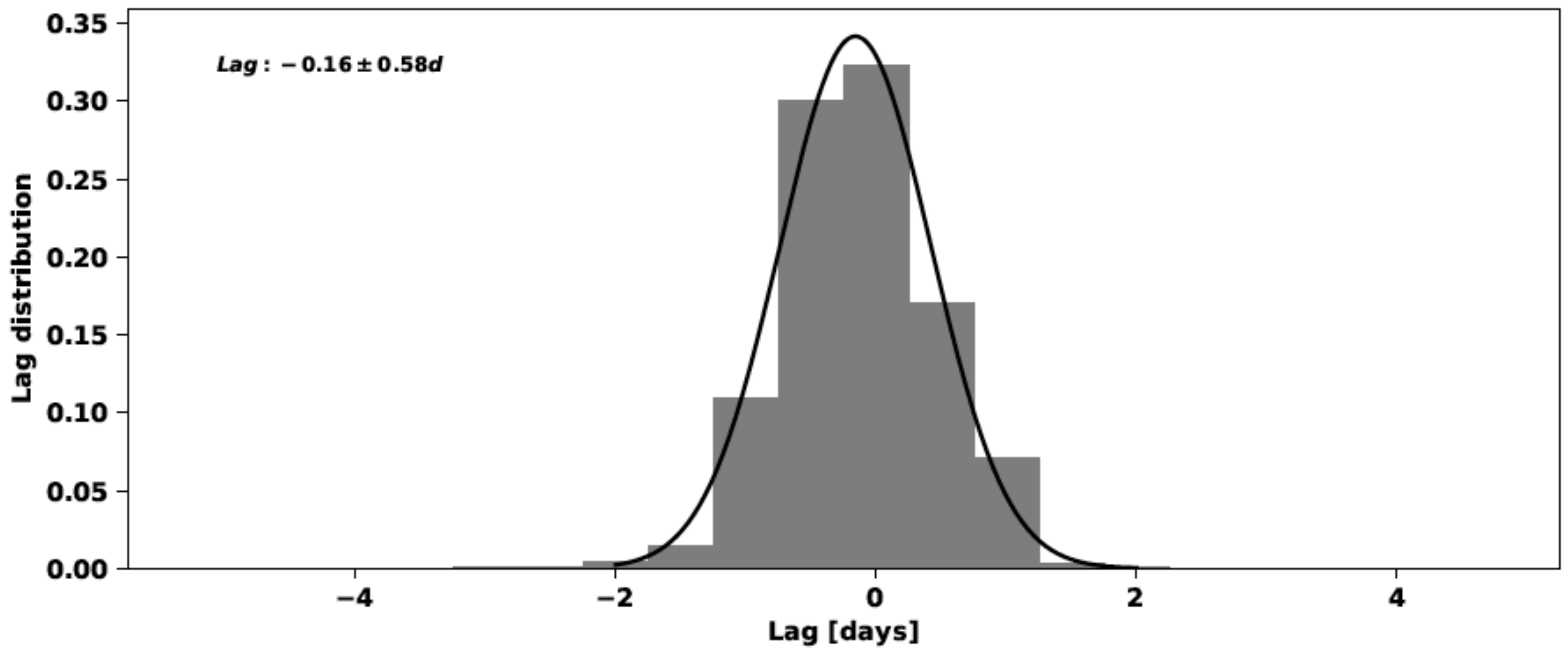
- Mrk 421 observations from December 2012 to April 2018
  - Mrk 421 was found in all states: typical, low, high
  - Data from radio to VHE (FACT), 9 instruments in total, unbiased observations



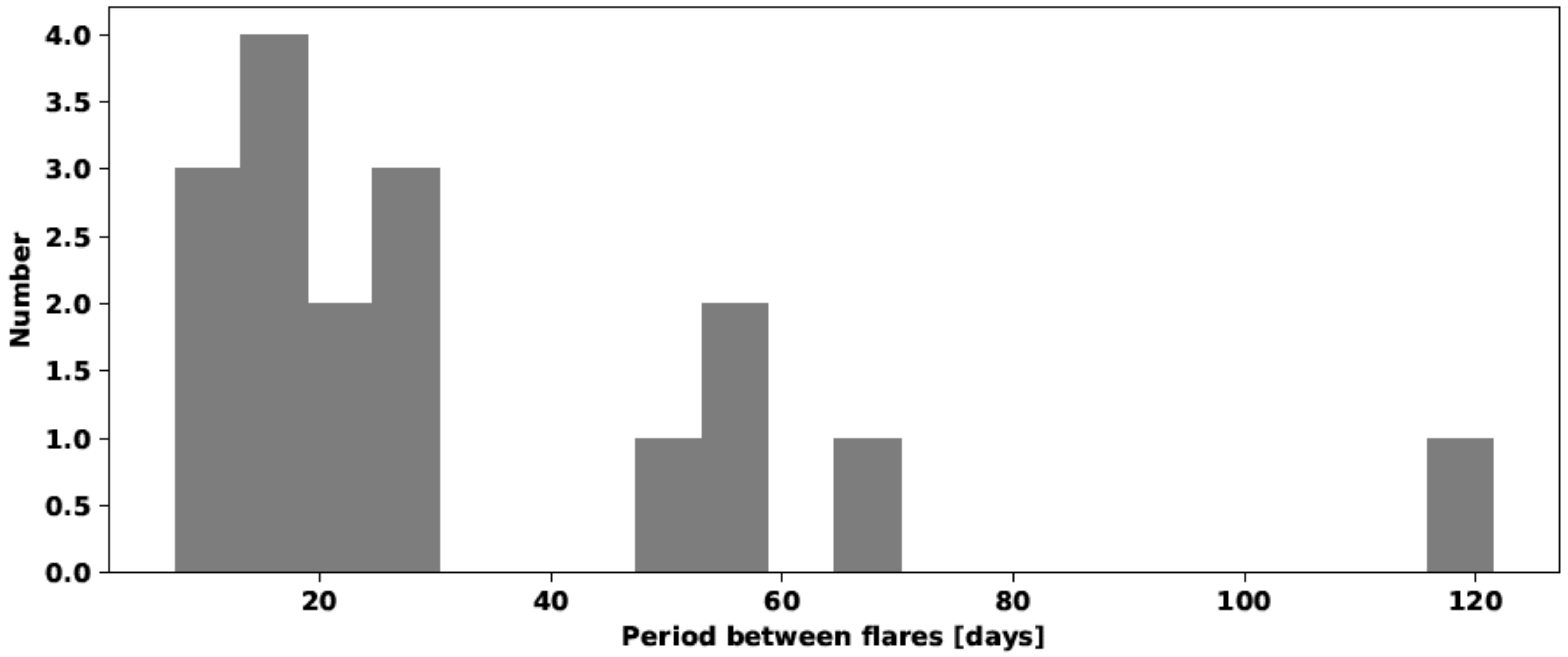


MWL campaigns: Arbet-Engels+MB+VS+RW, A&A, 2021

- Results:
  - F_{var} has a typical two peak structure:
    - lowest variability in radio and GeV
    - highest variability in X-rays and TeVs
  - X-rays are strongly correlated with TeVs with sub-day lag (<0.6 days)
  - Radio, optical and GeV are not correlated with X-rays or TeV
  - Radio, optical are widely correlated with GeV with later leading by 30-100 days.
  - Observed variability is compatible with one-zone SSC scenario
  - 22 individual TeV flares were identified:
    - distribution of time separation between those is peaking between 7.5 and 30 days
    - such time separation compatible with expected duration due to Lense–Thirring accretion disc precession



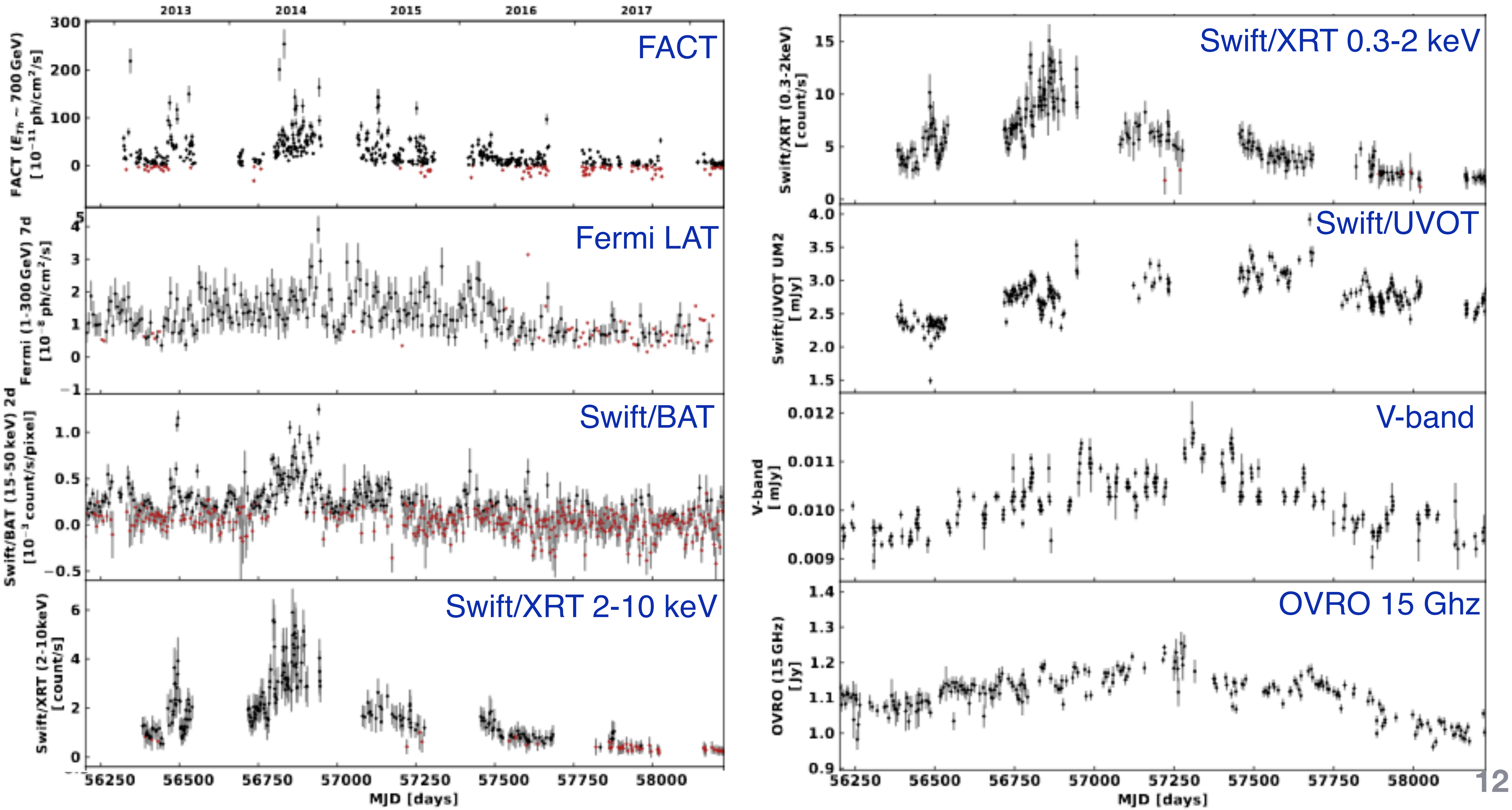
X-rays - TeV lag distribution



Inter-flare period for TeV flares

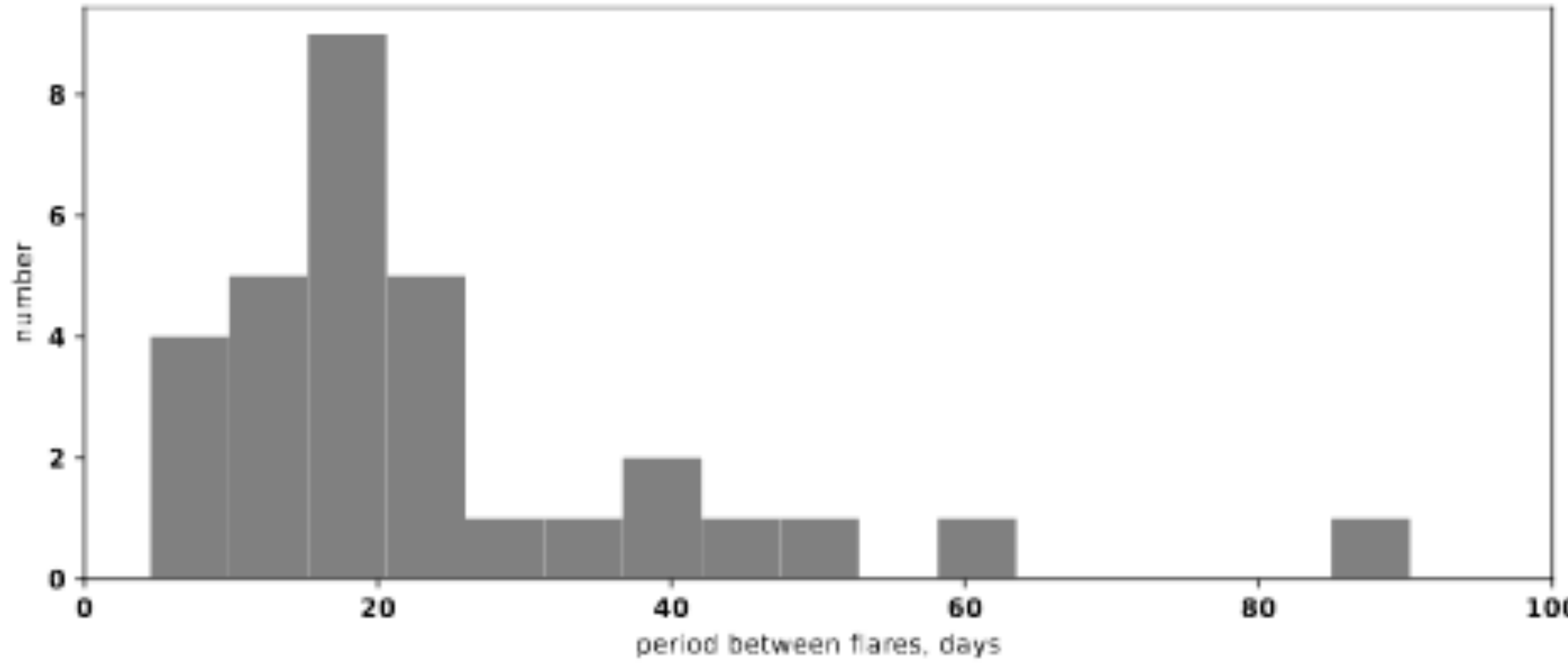
MWL campaigns: Fact Collaboration+VS+MB+RW, accepted in A&A

- Mrk 501 observations from December 2012 to April 2018
  - Mrk 501 was found in all states: typical, low, high
  - Data from radio to VHE (FACT), 8 instruments in total, unbiased observations

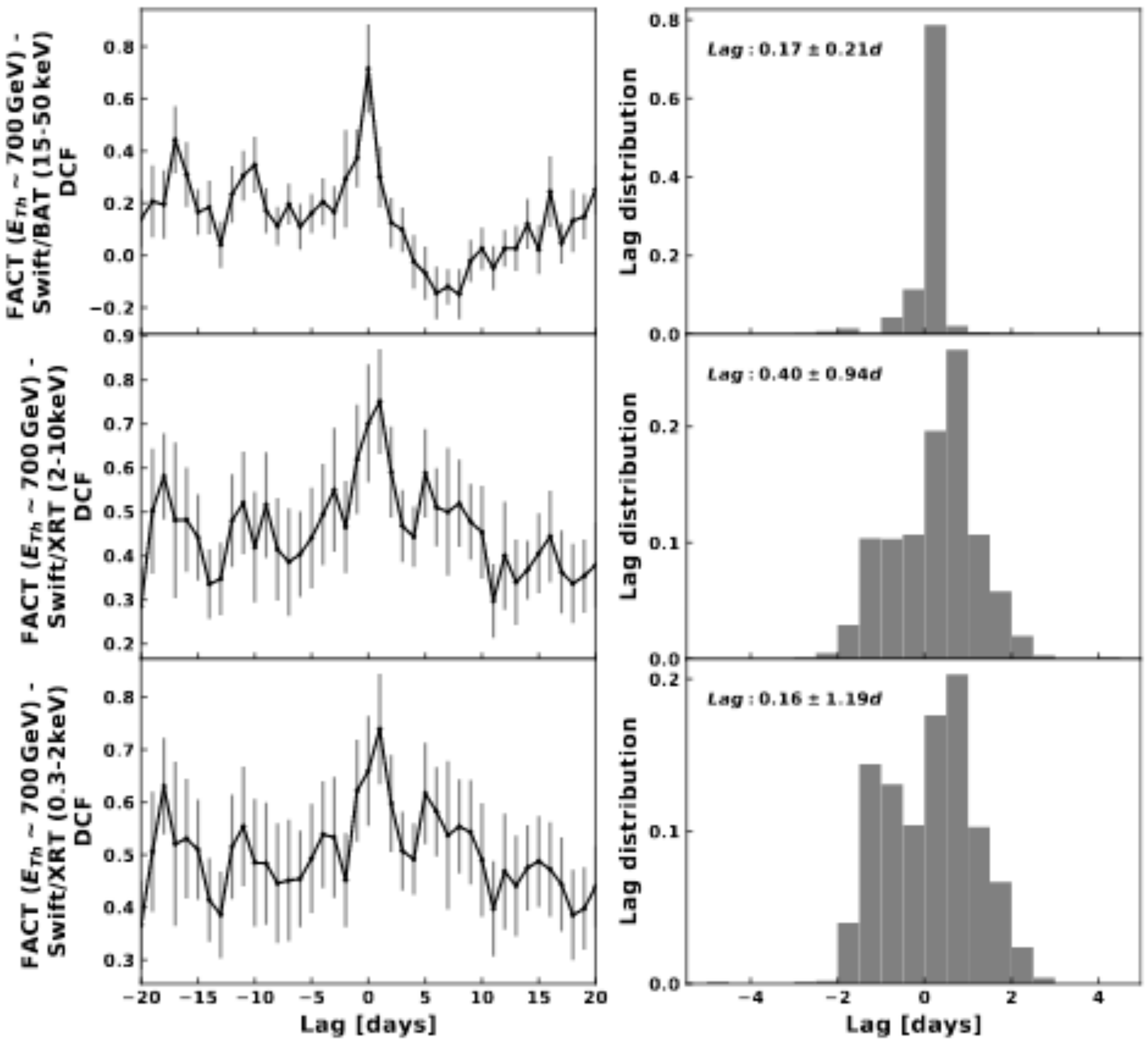


MWL campaigns: Fact Collaboration+VS+MB+RW, accepted in A&A

- Results:
  - F_{var} has a typical two peak structure:
    - lowest variability in radio and GeVs
    - highest variability in TeVs and X-rays
  - X-rays strongly correlated with TeVs with a sub-day lag (<0.4 days)
  - Radio, optical and GeV are not correlated with X-rays or TeV.
  - Radio, optical are widely correlated with GeV lagging by ~200 days.
  - Observed variability is compatible with one-zone SSC scenario
  - 37 individual TeV flares were identified:
    - distribution of time separation between them is peaking between ~15-20 days
    - such time separation compatible with expected duration due to Lense–Thirring accretion disc precession



Inter-flare period for TeV flares

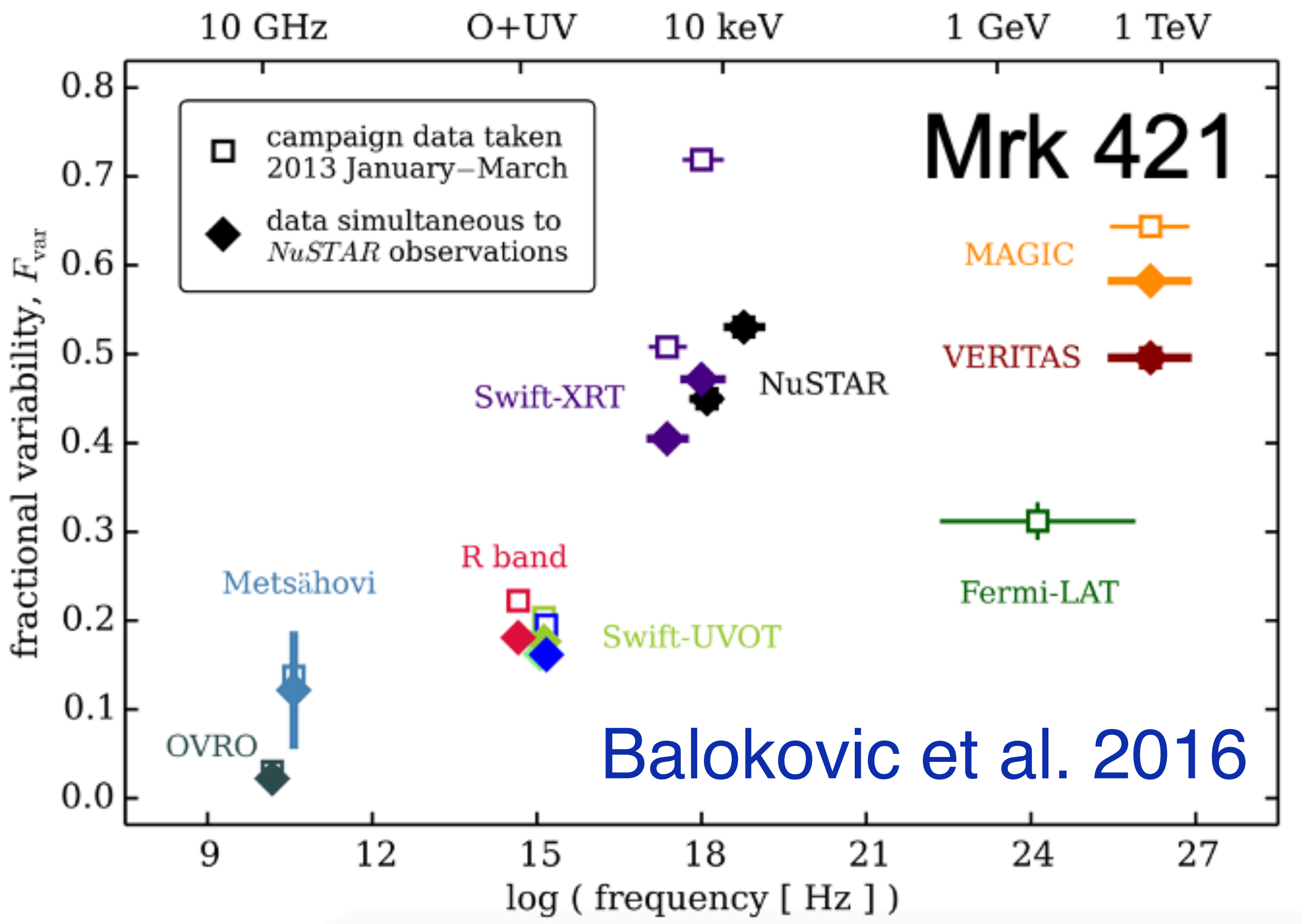


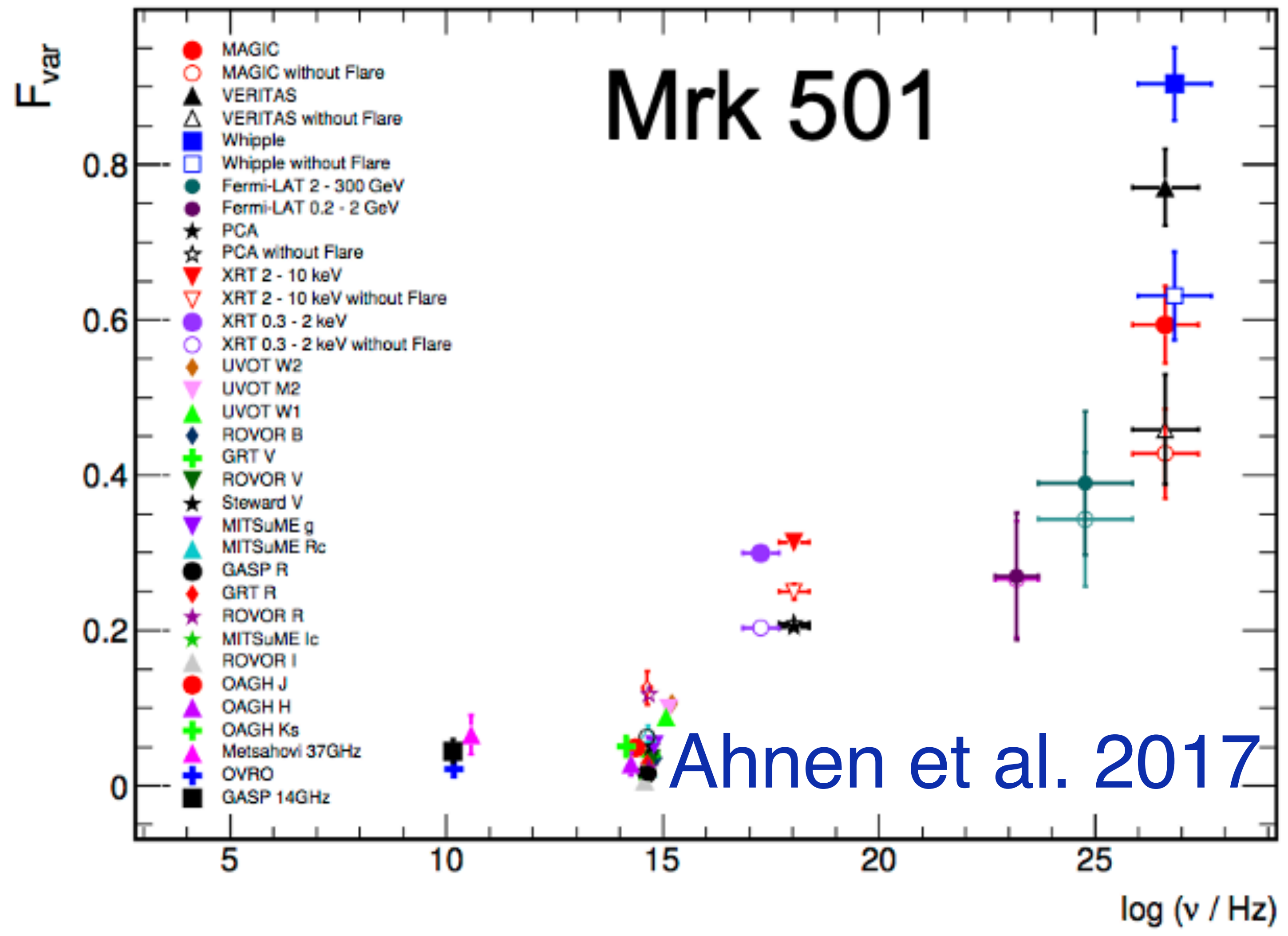
X-rays - TeV lag distribution and lag distributions

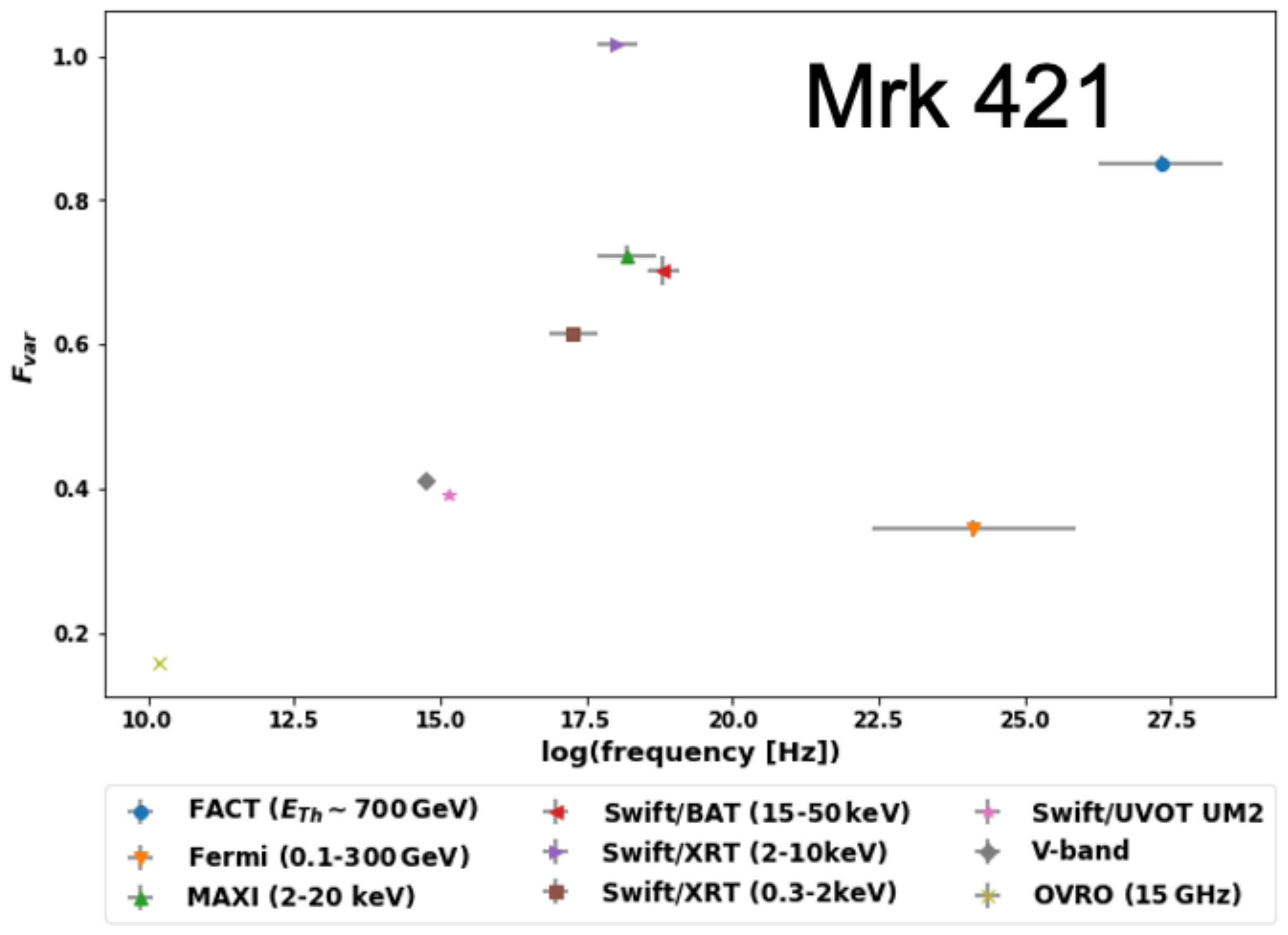
Mrk 421 and Mrk 501 variability

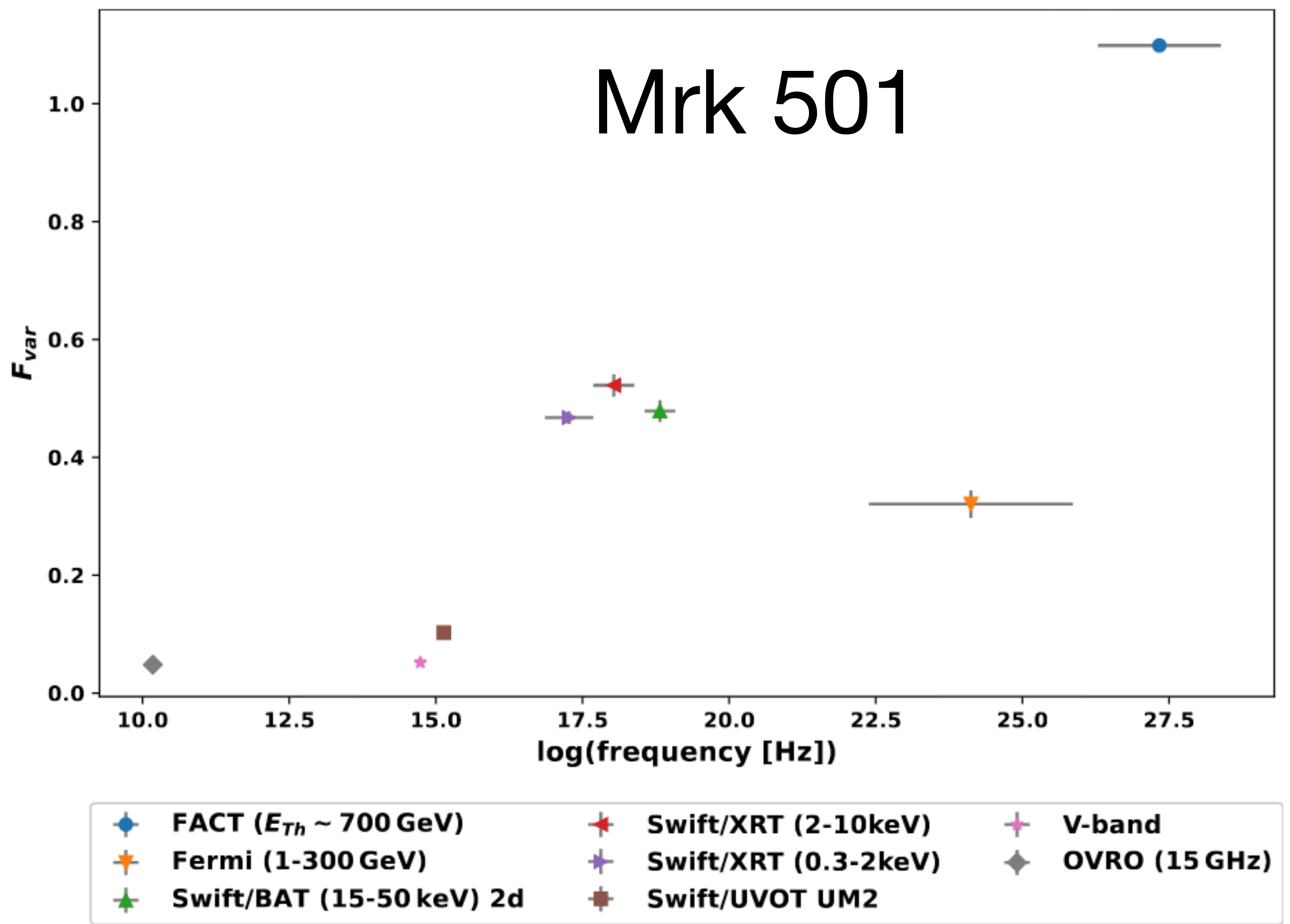
$$F_{var} = \sqrt{\frac{S - \langle \sigma_{err} \rangle^2}{\langle Flux \rangle^2}}$$

- "Falling segments" of the low- and high-energy bumps of SED are more variable than "rising segments"
  - within the SSC, since X-ray and VHE are produced by the highest-energy electrons
  - highest variability in the X-ray and TeV band
- TeV and X-ray flares are coincident
- Mrk 501 has somewhat different variability pattern during flaring and long-term periods:
  - monotonic increase during flares
  - double-peaked on long-term (mixed states)









Conclusions

- Mrk 421:
  - Observed cooling times are compatible with the SSC and incompatible in X-rays and TeV with leptono-hadronic and hadronic models
  - X-ray and TeV flares are well correlated:
    - 93% of the TeV flares are coincident with X-ray ones
    - TeV-X-rays lag is 0.09±0.57 days
  - Radio emission lags behind GeV with a delay of ~40 days
- Mrk 501:
  - X-ray and TeV flares are well correlated:
    - only ~50% of the TeV flares are coincident with X-rays ones
    - TeV-X-rays lag is 0.31±0.38 days
  - Radio emission lags behind GeV with a delay of ~200 days
- Common for Mrk 421 and Mrk 501:
  - The strongest variability is in the X-ray and in the TeV bands
  - Long term observations are compatible with one-zone SSC model